**APPENDIX II:**

**n-p-d-gamma**

**LIQUID HYDROGEN TARGET**

**POSSIBLE FAILURES RELATED TO HYDROGEN SAFETY**

**NOTES**

LIKELIHOOD LEVEL ABBREVIATIONS:

**5** Frequent (“Happened to you many times.”) (Expected once in 1-10 tries)

**4** Probable (“Happened to you once.”) (Expected once in 10-100 tries)

**3** Occasional (“Was a near-miss to you.”) (Expected once in $10^2$-$10^4$ tries)

**2** Improbable (“Happened once to someone you know”) (Expected once in $10^4$-$10^6$ tries)

**1** Remote (“Happened once, long ago, at another facility”).(Expected once in $10^6$-$10^8$ tries)

SEVERITY LEVEL ABBREVIATIONS

Note: Some scale of severity related to equipment damage is needed.

**4** Catastrophic (Death, coma, loss of limb, loss of sight) (Closing TA-53)

**3** Critical (Broken bones, bad cuts, 3rd degree burns, unconsciousness, out of work 1 week to 1 month) (Major stand down)

**2** Moderate (2nd degree burns, out of work 1 day to 1 week, work restrictions up to 1 week) ( ___________________ )

**1** Negligible (No lost work days, work restrictions up to 1 day) ( _______________ )

**IS** = Initial Severity

**IL** = Initial Likelihood

**RS** = Residual Severity

**RL** = Residual Likelihood

## A COMPONENT RUPTURES

**1** **System** LH2

**Component** Target flask or piping inside vacuum vessel

**Failure** Rupture – due to material or weld failure

**Result** LH2 release to vacuum vessel.
Rapid pressure rise in vacuum vessel and flask. Possible overpressure rupture of vacuum vessel.

**Initial Severity** **1** IF no vacuum vessel or relief failures **Initial Likelihood** **2**

**Failure Mitigation** Design to ASME code.
Use certified materials.
Use certified welders.
Radiograph welds.
Pressure test final assembly.
Vacuum vessel is secondary container. Design it and its relief system to handle full rupture of LH2 flask.
Do full operational test of system with LH2, simulating flask failures.

**Residual Severity** **1** **Residual Likelihood** **1**

**2** **System** LH2

**Component** Target flask or piping inside vacuum vessel

**Failure** Rupture – due to overpressure (inadequate relief capacity)

**Result** LH2 release to vacuum vessel.
Rapid pressure rise in vacuum vessel. Possible overpressure rupture of vacuum vessel

**Initial Severity** **1** IF no vacuum vessel or relief failures **Initial Likelihood** **2**

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| | **Failure Mitigation** | See Item A.1.<br>Design LH2 vent lines and relief valve capacity carefully for max. credible heat load.<br>Design to ASME code.<br>Design using highest pressure and thickest materials consistent with physics goals.<br>Use redundant relief valves.<br>Use two vent paths<br>Vacuum vessel is secondary container. Design it and its relief system to handle full rupture of LH2 **flask.**<br>Pressure test final assembly.<br>Do full operational test of system with LH2, simulating vessel failures. | | |
| | **Residual Severity** | 1 | **Residual Likelihood** | 1 |
| **3** | **System** | Vacuum jacket | | |
| | **Component** | Main vacuum vessel, vacuum piping | | |
| | **Failure** | Rupture – due to material or weld failure | | |
| | **Result** | He or air, depending on location of break, floods insulating space; high heat load on LH2 flask.<br>If H2 vessel ruptures, have air/H2 mixture in vacuum space; see Contaminants section | | |
| | **Initial Severity** | **1** if LH2 system does not rupture. See Item A.2<br>**3** (conflagration) or **4** (explosion) if H2/air mixture in vacuum space.<br>**4** if LH2 flask and helium jacket rupture | **Initial Likelihood** | 2 |
| | **Failure Mitigation** | See Items A.2, C.1.<br>Design to ASME code.<br>Use certified materials.<br>Use certified welders.<br>Radiograph welds<br>Surround vacuum jacket and piping with helium jacket so that vacuum space will be filled with helium, not air.<br>For piping that is difficult to enclose in helium jacket, build from very strong, reliable components (e.g., all welded, double bellows sealed valves, VCR fittings, etc.).<br>Pressure test final assembly.<br>Do full operational test of system with LH2, simulating vessel failures.<br>Install 2 speed fan to evacuate H2. | | |
| | **Residual Severity** | 1 | **Residual Likelihood** | 1 |
| **4** | **System** | Vacuum jacket | | |
| | **Component** | Main vacuum vessel, vacuum piping | | |
| | **Failure** | Rupture – due to *external* pressure (from helium jacket) | | |
| | **Result** | He floods insulating space; high heat load on LH2 flask. | | |

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| | **Initial Severity** | **1** if LH2 system does not rupture. See Item A.2<br>**4** if LH2 flask and helium jacket rupture | **Initial Likelihood** | **2** |
| | **Failure Mitigation** | See Item A.3.<br>Design to ASME code.<br>Design for appropriate external pressure.<br>Design helium jacket pressure control and relief system appropriately to avoid high external pressures. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **5** | **System** | Vacuum jacket | | |
| | **Component** | Main vacuum vessel and piping | | |
| | **Failure** | Rupture – due to *internal* pressure (e.g., when LH2 flask ruptures) | | |
| | **Result** | LH2 release to helium jacket.<br>Rapid pressure rise in helium jacket and LH2 flask, with possible overpressure rupture | | |
| | **Initial Severity** | **1** if helium jacket or vacuum piping do not rupture<br>**4** if helium jacket ruptures | **Initial Likelihood** | **2** |
| | **Failure Mitigation** | See Items A.1, A.2.<br>Design vacuum vessel vent line and relief valve capacity carefully for max. credible gas evolution rate.<br>Design to ASME code.<br>Design using highest pressure and thickest materials consistent with physics goals.<br>Design for appropriate internal pressure.<br>Use redundant relief valves.<br>Design helium jacket relief system appropriately<br>Do full operational test of system with LH2, simulating vessel failures.<br>Install 2-speed fan to evacuate H2. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **6** | **System** | LN2 precooler | | |
| | **Component** | Vessel, piping | | |
| | **Failure** | Rupture – due to overpressure (inadequate relief capacity) | | |
| | **Result** | LN2 release to vacuum vessel.<br>Rapid pressure rise in vacuum vessel and large heat load on LH2 flask.<br>Possible overpressure rupture of vacuum vessel and/or LH2 flask. | | |
| | **Initial Severity** | **1** | **Initial Likelihood** | **2** |

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| | **Failure Mitigation** | Design LN2 vent line and relief valve capacity carefully for max. credible heat load.<br>Design to ASME code.<br>Use redundant relief lines and valves.<br>Vacuum vessel is secondary container. Design it and its relief system to handle full rupture of precooler system.<br>Consider locating LN2 precooler outside main vacuum vessel – or – replacing LN2 bath with connection to one of the refrigerators.<br>Pressure test final assembly.<br>Do full operational test of system with LH2, simulating vessel failures. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |

## B COMPONENT FAILURES

| | | | | |
|---|---|---|---|---|
| **1** | **System** | Refrigerator | | |
| | **Component** | Any | | |
| | **Failure** | Cooling failure (either device or power failure) | | |
| | **Result** | H2 pressure rises slowly. Heat load is much lower than maximum credible failure. Relief valves open. No safety problems, only operational problems. | | |
| | **Initial Severity** | **1** | **Initial Likelihood** | **4** |
| | **Failure Mitigation** | Redundant refrigerators or auxiliary generator, if importance to experiment operation justifies the cost. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **2** | **System** | Refrigerator | | |
| | **Component** | Temperature controller | | |
| | **Failure** | Fails low | | |
| | **Result** | LH2 freezes. Possible line plugging with frozen hydrogen.<br>Possible reduction of H2 gas pressure below atmospheric, with increased risk of drawing in air/contaminants. | | |
| | **Initial Severity** | **1** | **Initial Likelihood** | **3** |
| | **Failure Mitigation** | Interlock target pressure and temperature sensors to alarm and possibly to refrigerator shutoff.<br>Surround H2 system with helium jacket, or build from very strong, reliable components (e.g., all welded, double bellows sealed valves, VCR fittings, etc.).. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **3** | **System** | Refrigerator | | |
| | **Component** | Temperature controller | | |
| | **Failure** | Fails high | | |

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| | **Result** | Inadequate cooling. If refrigerator is ON, gives extra heat load on LH2 system.<br>If refrigerator is OFF, could cause very hot local spot in piping , possibly weakening piping, damaging heater, or causing electrical short to ground. | | |
| | **Initial Severity** | **1** | **Initial Likelihood** | **4** |
| | **Failure Mitigation** | Interlock temperature controller to refrigerator operation and/or flask temperature. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **4** | **System** | Vacuum jacket | | |
| | **Component** | Relief valve(s) | | |
| | **Failure** | Fails to open or opens only partially | | |
| | **Result** | High pressure in vacuum jacket. Possible rupture. Possible damage to or collapse of LH2 flask if source of gas is LN2 precooler failure<br>H2 release to helium jacket (if vaqcuum jacket ruptures) or to air (if vacuum piping or pumping system rupture), if gas source is LH2 flask failure.<br>Rapid pressure rise in helium jacket, with possible overpressure rupture | | |
| | **Initial Severity** | **1** if helium jacket or vacuum piping do not rupture<br>**4** if H2 is released to cave<br>**3** if N2 is released to cave or H2 is released outside cave | **Initial Likelihood** | **2** |
| | **Failure Mitigation** | Use ASME code relief valves or devices with equal reliability.<br>Use redundant relief valves.<br>Design helium jacket relief system appropriately for vacuum jacket rupture | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **5** | **System** | LH2 flask | | |
| | **Component** | Relief valve(s) | | |
| | **Failure** | Fails to open or opens only partially | | |
| | **Result** | High pressure in LH2 flask. Possible rupture.<br>LH2 release to vacuum jacket Rapid pressure rise in vacuum jacket, with possible overpressure rupture | | |
| | **Initial Severity** | **1** if vacuum jacket or vacuum piping do not rupture<br>**4** if H2 is released to cave<br>**3** if H2 is released outside cave | **Initial Likelihood** | **2** |
| | **Failure Mitigation** | Use ASME code relief valves or devices with equal reliability.<br>Use redundant relief valves.<br>Design vacuum jacket relief system appropriately for H2 flask rupture | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |

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| **6** | **System** | Helium jacket | | |
| | **Component** | Relief valve(s) | | |
| | **Failure** | Fails to open or opens only partially | | |
| | **Result** | High pressure in helium jacket. Possible rupture. Possible damage to or collapse of vacuum jacket if source of gas is He supply failure.<br>H2 release to cave air if He jacket ruptures and gas source is LH2 flask failure.<br>N2 release to cave air if He jacket ruptures and gas source is LN2 precooler failure.<br>He release to cave air if source is He supply gas failure. | | |
| | **Initial Severity** | **1** if helium jacket does not rupture<br>**4** if H2 is released to cave<br>**3** if N2 is released to cave<br>**2** if He is released to cave | **Initial Likelihood** | **2** |
| | **Failure Mitigation** | Use ASME code relief valves or devices with equal reliability.<br>Use redundant relief valves.<br>Design helium jacket relief system appropriately for vacuum jacket rupture or He supply system failure. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **7** | **System** | Vacuum jacket | | |
| | **Component** | Vessel or piping | | |
| | **Failure** | Damage/rupture from shrapnel created by rupture of the LH2 flask or LN2 precooler inside | | |
| | **Result** | See Items on rupture of vacuum jacket from other causes.<br>LH2 release to cave IF helium jacket also ruptures | | |
| | **Initial Severity** | **1** if helium jacket stays intact.<br>**4** if helium jacket ruptures | **Initial Likelihood** | **2** |
| | **Failure Mitigation** | Use ductile materials for all vessels at all temperatures.<br>Design to ASME code.<br>Do full operational test of system with LH2, simulating vessel failures. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **8** | **System** | Helium jacket | | |
| | **Component** | Vessel or piping | | |
| | **Failure** | Damage/rupture from shrapnel created by rupture of the vessel inside | | |
| | **Result** | LH2 release to cave<br>See Items on rupture of vacuum jacket from other causes. | | |
| | **Initial Severity** | **4** | **Initial Likelihood** | **2** |
| | **Failure Mitigation** | Use ductile materials for all vessels at all temperatures.<br>Design to ASME code.<br>Do full operational test of system with LH2, simulating vessel failures. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |

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| **9** | **System** | H2 gas handling system | | |
| | **Component** | Pipes inside cave but outside He jacket | | |
| | **Failure** | Broken or leaking | | |
| | **Result** | H2 release into cave | | |
| | **Initial Severity** | **2** if leaking<br>**3 or 4** if broken | **Initial Likelihood** | 2 |
| | **Failure Mitigation** | Enclose all piping with joints inside the helium jacket with adequate relief capacity<br>Protect all pipes from mechanical damage. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **10** | **System** | H2 gas handling system | | |
| | **Component** | Pipes outside cave | | |
| | **Failure** | Broken or leaking | | |
| | **Result** | H2 release into ER2 | | |
| | **Initial Severity** | **1** if leaking<br>**2** if broken | **Initial Likelihood** | 2 |
| | **Failure Mitigation** | Enclose all joints inside a helium vessel with adequate relief capacity venting outside ER2 – OR-- build from very strong, reliable components (e.g., all welded, double bellows sealed valves, VCR fittings, etc.).<br>Protect all pipes from mechanical damage.<br>Evacuate H2 and backfill with He all pipes that are not in use during a particular phase of operation. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **C** | **CONTAMINANTS** | | | |
| **1** | **System** | LH2 | | |
| | **Component** | Target flask or piping inside the vacuum jacket. | | |
| | **Failure** | Plugged vent line -- due to freezing of contaminants | | |
| | **Result** | Rupture – due to overpressure<br>LH2 release to vacuum vessel.<br>Rapid pressure rise in vacuum vessel. Possible overpressure rupture of vacuum vessel. | | |
| | **Initial Severity** | **1** IF no vacuum vessel or relief failures and redundant relief line is open. | **Initial Likelihood** | 4 |

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| | **Failure Mitigation** | See item A.2.<br>Verification of purge completeness.<br>Use redundant vent lines.<br>Use certified feed gas and input gas cleanup.<br>Helium jacket all H2 lines where practical.<br>Weld all joints and use high reliability components on all H2 lines where He jacket is impractical.<br>Have thorough leak check procedures.<br>Have thorough procedures to remove contaminants from H2 system before cooldown.<br>Helium purge on discharge side of all relief devices. | | |
| | **Residual Severity** | 1 | **Residual Likelihood** | 1 |
| 2 | **System** | Vacuum jacket | | |
| | **Component** | All | | |
| | **Failure** | Air leak – large or small (due to any cause, but probably to leakage of vacuum piping outside the He jacket or to operator error). | | |
| | **Result** | High heat load on LH2 flask if large air leak.<br>Low heat load on LH2 flask if small air leak.<br>Possible air/H2 mixture in vacuum vessel if flask ruptures | | |
| | **Initial Severity** | **1,** if LH2 system does not rupture. See Item A.2<br>**3 or 4** if H2/air mixture in vacuum space. | **Initial Likelihood** | 2 |
| | **Failure Mitigation** | See Items A.2, A.3, A.4, C.1, E.___<br>Design to ASME code.<br>Surround vacuum jacket and piping with helium jacket so that vacuum space will be filled with helium, not air.<br>Pressure test final assembly.<br>Do full operational test of system with LH2, simulating vessel failures. | | |
| | **Residual Severity** | 1 | **Residual Likelihood** | 1 |
| 3 | **System** | Vacuum jacket | | |
| | **Component** | All | | |
| | **Failure** | Helium leak – large or small | | |
| | **Result** | See items on vacuum jacket failure, A.3, A.4<br>Large leak -- He floods insulating space; high heat load on LH2 flask.<br>Small leak -- He invades insulating space; moderate heat load on LH2 flask. | | |
| | **Initial Severity** | **1** if LH2 system does not rupture. See Item A.2<br>**4** if LH2 flask and helium jacket rupture | **Initial Likelihood** | 2 |
| | **Failure Mitigation** | Design and build LH2 flask, piping, and relief system appropriately.<br>Do full operational test of system with LH2, simulating vessel failures. | | |
| | **Residual Severity** | 1 | **Residual Likelihood** | 1 |

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|---|---|---|---|---|
| **4** | **System** | H2 gas handling system | | |
| | **Component** | All | | |
| | **Failure** | Air leaks – small or large | | |
| | **Result** | Air/H2 mixture inside H2 system.<br>Plugs in piping to cold regions. See Item C.1<br>Result for small and large leaks is same, except that everything happens faster for large leaks and there is greater potential for combustible H2/O2 mixtures. | | |
| | **Initial Severity** | **1** IF no vacuum vessel or relief failures and redundant relief line is open.<br>**2 to 3** if combustible mixture is formed. | **Initial Likelihood** | **2** |
| | **Failure Mitigation** | See item A.2, C.1<br>Use redundant vent lines.<br>Leak check all joints and components carefully at assembly.<br>Helium jacket all H2 lines where practical.<br>Weld all joints and use high reliability components on all H2 lines where He jacket is impractical.<br>Helium purge on discharge side of all relief devices.<br>Do periodic leak check procedures. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |

| **D** | **FIRES, NATURAL EVENTS** | | | |
|---|---|---|---|---|
| **1** | **System** | ER2 | | |
| | **Component** | General area of target system | | |
| | **Failure** | Fire | | |
| | **Result** | Increased fire severity if H2 gas is released | | |
| | **Initial Severity** | **2** | **Initial Likelihood** | **1** |
| | **Failure Mitigation** | Building sprinkler system.<br>Good housekeeping.<br>Local fire extinguishers<br>Initiate LH2 “fast empty” system | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **2** | **System** | ER2 | | |
| | **Component** | All of H2 target system | | |
| | **Failure** | Earthquake | | |
| | **Result** | Possible line breakage and H2 release | | |
| | **Initial Severity** | | **Initial Likelihood** | |
| | **Failure Mitigation** | Secure all components appropriately.<br>Survey for adequate installation before system operation. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |

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| **3** | **System** | H2 vent line | | |
| | **Component** | | | |
| | **Failure** | Fire at exit of vent line | | |
| | **Result** | Possible combustion into vent pipe if air/H2 mixture exists.<br>Possible ignition of materials near vent exit. | | |
| | **Initial Severity** | **2** | **Initial Likelihood** | **2** |
| | **Failure Mitigation** | Put vent line check valve close to exit to minimize length/volume of air/H2 mixture.<br>Purge line between relief valves and check valve with helium.<br>Locate vent stack in safe area. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **4** | **System** | Electrical power | | |
| | **Component** | All | | |
| | **Failure** | Interruption | | |
| | **Result** | Possible unintended valve operation.<br>Loss of refrigeration.<br>Loss of system status indication.<br>Loss of cave ventilation | | |
| | **Initial Severity** | **2** | **Initial Likelihood** | **5** |
| | **Failure Mitigation** | Use Power-To-Open valves where appropriate.<br>Use Power-To-Close valves where appropriate.<br>Use mechanical gages as appropriate.<br>All personnel out of cave during power outage. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **5** |
| **E** | **OPERATIONAL ERRORS** | | | |
| **1** | **System** | Vacuum | | |
| | **Component** | Valve | | |
| | **Failure** | Operator opens with vacuum pump not running and H2 system cold. | | |
| | **Result** | Large flood of air into vacuum space, large heat load on LH2 system.<br>See A.3, etc. | | |
| | **Initial Severity** | **1** if no LH2 system or relief failures | **Initial Likelihood** | **4** |
| | **Failure Mitigation** | Interlock valve operation with refrigerator.<br>Close valve when LH2 system is cold. | | |
| | **Residual Severity** | **1** | **Residual Likelihood** | **1** |
| **2** | **System** | H2 gas, vacuum, helium, refrigerator, etc. -- CONTROLS | | |

**APPENDIX II:**

## n-p-d-gamma
## LIQUID HYDROGEN TARGET
## POSSIBLE FAILURES RELATED TO HYDROGEN SAFETY

Controls should not have any bearing since all systems are designed to be self-contained and will fail safe. Computer control can serve as a warning and initiate actions, but if it fails the final system such as reliefs and valves which fail closed (supply) or fail open (return) should always be safe.